Importance of 3D and Inkjet Printing For Tony Stark and the Iron Man Suit

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IMPORTANCE OF 3D AND INKJET PRINTING FOR TONY STARK AND THE IRON MAN SUIT

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ABSTRACT

For decades we have used printers to print superheroes on the pages of comic books but could printing technologies actually be used to print real life superheroes? 3D and functional printing technologies have advanced greatly in recent years and even though these technologies cannot be used to print heroes themselves, they can certainly be used for equipment manufacturing. One character that could or may use 3D printing to rapidly produce prototypes and final versions of new technologies is Tony Stark. As the inventor and primary user of the Iron Man suit, Stark has designed a wearable suit that is not only a weapon but also protects him. However, in battle the suit can become damaged and require urgent repairs. To aid in these repairs, Tony Stark could turn to 3D printing technologies to produce new components for the suit. In this paper we will outline 3D printing technologies and describe their current applications. We will then discuss how 3D printing is being used to print electronics and the ramifications for Tony Stark, his Iron Man suit and the potential use for a real Iron Man suit.

PROLOGUE

Back in the Avengers compound, Stark assesses the damage. As he turns the helmet in his hands, flecks of Hot Rod Red paint fall to the floor, shimmering as they catch the sunlight from a nearby window. The right arm of the suit has sustained severe damage. It's time to start the repairs. It's time to 3D print.

INTRODUCTION

The Iron Man suit is one of the most famous inventions in the superhero comic books and Hollywood films. Developed by Tony Stark, the suit allows the wearer to fly thanks to thrusters in the boots and gauntlets or gloves, protects the wearer, has advanced computing systems

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and a number of weapons located around the suit. The suit even includes a mobile phone and can be controlled over the Internet as shown in the 2017 film *Spider-Man: Homecoming* [1]. Alongside Spider-Man's web slingers and Batman's Batmobile, the Iron Man suit is one of the foremost superhero technologies that many people around the world would like to have at home [2].

In the 2008 film *Iron Man* [3], Tony Stark built the Mark I Iron Man suit in a cave in Afghanistan from sheet metal in a process that took many hours. This was a tough manufacturing approach undertaken by Stark and while the Mark I suit allowed him to escape his captors, it was big, clunky and not very aerodynamic. After returning home, Stark designed and built the Mark II suit, which turned out to be a sleeker and much more reliable suit. Although Tony did not have to hammer sheet metal to make the Mark II suit, he still had to use manufacturing methods that might have been used in industry, and this would have taken some time. Over the years, Stark has faced off against many villains, and even heroes, in the films and comic books. For example, in the 2012 film *The Avengers* [4], Iron Man faces off against an alien invasion in New York City, while in the 2015 film *Avengers: Age of Ultron* [5], he battles Ultron, an artificial intelligence focused on destroying the planet. In the 2018 film *Avengers: Infinity War* [6], he fights the powerful Thanos. After such battles, unlike other Avengers such as Captain America [7] and Hawkeye [8-10] whose powers are biologically based, Stark must repair his suit before using it once again. If the suit does not operate correctly then he is just plain and simple Tony Stark, a man without any inherent superpowers. This means that he needs a fast way to repair his suits and, if required, make new parts for the suit. One approach that Tony Stark could use to swiftly build parts for the Iron Man suit is 3D printing technologies.

INTRODUCTION TO 3D PRINTING

Nowadays, 3D printing is a very common term that can refer to anything that has been manufactured by a machine from a digital design model by adding layers of material on top of layers of material. The standard ISO/ASTM 52900 defines the general principles and terminology that are widely used [11]. However, in this article, we will use the term 3D printing as a broad term and another phrase for additive manufacturing. We will review two very different approaches and uses for additive manufacturing or 3D printing technologies. First, we consider 3D printing as used for various materials and second, we will look at the printing of functional materials that could be used in electronic devices. In the section on 3D printing, we will focus on the manufacturing of physical structures such as golf balls, while the section on functional printing covers the printing of materials that can be used to perform specific functions. In the ideal case, a hybrid printing technology, involving the printing of both functional and structural materials in a 3D printer platform would be highly desirable.

3D PRINTING

Undoubtedly 3D printing has received considerable attention in recent years [12]. The technology has become cheaper, and thus more accessible to more and more people, and has allowed for the rapid manufacturing of dependable equipment and tools. Most 3D printers currently available to the general public print plastic materials due to their easy processing and low price. 3D printing, in general, consists of a wide selection of techniques that allow for the processing of materials such as metals, concrete, paper, ceramics, glass and even edible ingredients like chocolate [13]. Each material type has tailored manufacturing requirements for the successful manufacturing of parts and structures. Prior to printing, the structure of a part is designed using computer aided design (CAD) software. A typical 3D printer design is shown in Figure 1 with moving printhead and substrate table.

Figure 1: 3D printer design by LulzBot [14].

Depending on the material and product requirements, post-processing of the 3D-printed part may be needed. The simplest option is to use the part directly after printing. However, this is not always be possible as parts or materials themselves might need further processing to be usable. For metal parts, printed support structures may need removal and the parts can be subjected to a heat treatment cycle to prevent future deformation of the part. With heat treatments, ductility and impact resistance of the material are enhanced, which could be beneficial for many superheroes. For example, it would not be good if Captain America's vibranium shield cracks and breaks just like a brittle material without denting or if the Iron Man suit breaks under thermal and mechanical stresses of flight and combat.

Plastics can be 3D printed with fewer issues, as there is less of a need to print support structures during the build. In addition, the properties of plastics are different to metals or ceramics. When a plastic part that must include support structures is printed, a different plastic can be chosen for the support structures. This plastic can be dissolvable in a solvent while the primary plastic part remains unaffected. Ceramic 3D printing requires more caution in comparison to plastic or metal printing as the parts produced are much more brittle. Often a mixture of ceramic powder and plastic matrix is 3D printed to create a plastic-ceramic hybrid part. Afterwards, the item is heat-treated to remove the plastic and to fuse the ceramic particles.

There are several 3D printing techniques available, with each having unique benefits and disadvantages. Selection of the appropriate printing technique depends on the application requirements and materials to be printed. The most commonly used technique is known as Fused Deposition Modelling (FDM), which is based on material extrusion [11]. In material extrusion, the source material, usually a plastic filament is fed into a heated print head where it is melted. The plasticised thermoplastic is then extruded or pushed outwards from the print head layer by layer onto a build platform. The printing process is entirely computer controlled by moving either the nozzle or the build platform to achieve the desired 3D model. After deposition the material cools and becomes rigid [15, 16]. In this paper we will mainly focus on material extrusion techniques in 3D printing.

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Another 3D printing technology that can be used for plastics is stereolithography apparatus (SLA), whereby an object is made from a plastic resin by curing it with light source [17]. The 3D object is solidified with light from a laser [18, 19] or even a mobile phone [20] after which the object is lifted from the resin bath. After the build process, the part is weak and is cured with UV-light to strengthen it. SLA produced parts are smooth and have good optical properties, clear structure and a smooth outer layer, making them highly suitable for use as lenses in optical devices. For example, Formlabs clear resin can be used to 3D print lenses with SLA technology [21]. On the other hand, hard plastics, such as nylon (polyamide), are manufactured with laser sintering in which a laser selectively melts the part from a powder [19]. Parts created with laser sintering outperform FDM pieces in terms of material strength and homogeneity of material properties. Polymers used in laser sintering behave in a brittle fashion whereas polymers used in FDM are more ductile. In other words, laser sintered polymer pieces are harder and the shear strength is lower than ductile FDM specimens.

BENEFITS AND APPLICATIONS OF 3D PRINTING

Regardless of the technique, 3D printed pieces and components can be fabricated using less material and contain intricate internal details that would be almost impossible for a tool in a conventional manufacturing device to craft. A prime example of complicated parts are the turbine blades manufactured by Avio Aero for the jet engines [22]. These 3D printed engine blades includes cooling channels and a turbine nozzle where several individual parts have been integrated into a single part reducing manufacture costs, processing steps and time. In conventional tooling involving industrial machines, tools must be able to remove material from the part. However, in additive manufacturing, this is not required. As a result the product complexity can be increased without additional processing steps.

The freedom of design and material choice allows for the manufacture of hollow support structures with the mechanical strength and durability of bulk materials with a fraction of the weight. One material being used to create 3D structures is graphene, which is one of the strongest known materials. The discovery of graphene won the Nobel Prize in Physics in 2010 [23]. Researchers at Massachusetts Institute of Technology (MIT) have 3D printed a graphene metamaterial structure with a material density of only 5%. This means that only 5% of the entire volume of the object is made from graphene. Nonetheless, the structure has 10 times the strength of steel [24, 25]. The 3D printed graphene structure is shown in Figure 2.

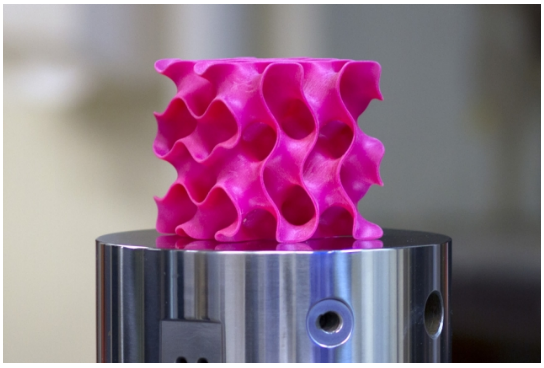

Figure 2: 3D printer graphene structure fabricated at MIT [24]. The size of this structure is roughly 7 cm by 7 cm.

The major drawback with 3D printing technologies is that any part produced is weaker along one direction in comparison to the other directions. For example, a part could be very strong when subject to shear or tangential forces. However, the same part could be extremely weak to normal forces, which are perpendicular to tangential forces. This effect is called anisotropy and presents unique challenges in the design and use of 3D printed products [26]. The different directions in building an object using 3D printing are indicated for the model of Captain America in Figure 3. From the figure it is clear that objects are built along the *z*-direction.

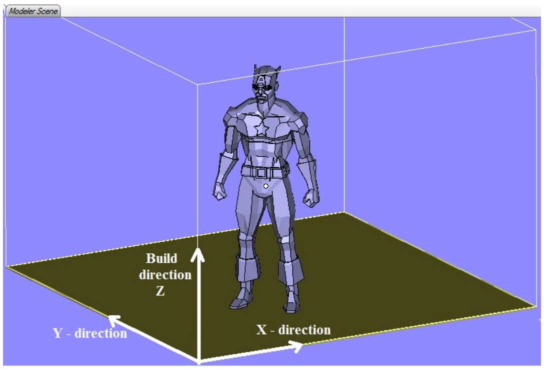

Figure 3: Image created using Materialise Magics [27] using a stereolithography (STL) file downloaded from Cults3d [28]. If Tony Stark needed to print objects for his suit on the fly, it is possible that he could download STL files from his servers at Stark Tower and print the designs using portable 3D printing technologies.

3D printed parts and products are weakest in the *z*-direction or along the height of the material, which is the plane over which the material layers are added. This layer printing can create a weak spot during the build and lead to local mechanical weakening of the part. In the case of FDM, each layer of polymer chains is extruded from the nozzle in one direction. Mechanical weakening is caused by the inability of new layer to exactly join with the previous layer below it. In FDM, when printing with acrylonitrile butadiene styrene (ABS), the tensile strength of the material is halved with moving from printing along the *x*-direction to along the *z*-direction [29]. Such a change can have large effects on the print quality. In addition, defects, such as missing layers, can be created, which significantly lower the part uniformity. Anisotropy is also present in other 3D printing methods. However, with metals and ceramics, post treatment can be applied to reduce the effect of the anisotropy.

3D printing of composite structures is also possible with hybrid 3D manufacturing methods and combining different manufacturing methods. Layer-by-layer fabrication can lead to large variations within a part that is completely printed using one process. Hollow structures with closed surfaces can be created to optimise the mechanical load distribution evenly in the material, and therefore reduce the mass of the material. Microstructure in metals can also be tailored depending on the application and additional functional layers can be added on top of materials. For example, a 3D printing robot can extrude, weld or spray different materials on top of a substrate, thus creating a hard thermal insulating coating [30]. Such a thermal insulating coating would be highly important for Tony Stark and the Iron Man suit. It could protect Stark's body, particularly his legs, back and hands, from the extreme heat coming from the use of his flight thrusters. He certainly would not want to be burnt while using the suit!

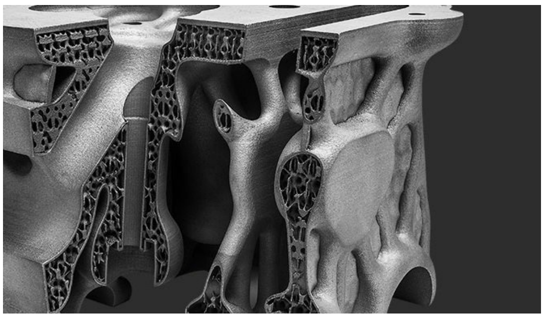

Figure 4: 3D printed engine cylinder head [31].

An example of a 3D printed structure that accounts for issues with mass and thermal energy is the engine cylinder head shown in Figure 4. By changing to an additive design and using 3D printing, the mass of the cylinder head was reduced by over 65%, while also increasing the cooling surface area by 635% and reducing the mechanical vibrations [31]. This demonstrates the benefits of hollow internal structure over traditional block-based manufacturing. Tony Stark could also employ a similar approach to increase surface cooling of the Iron Man suit, particularly in areas near the flight thrusters.

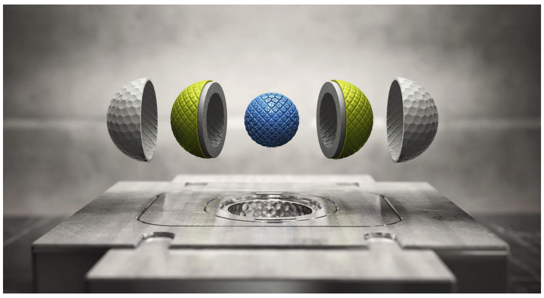

Figure 5: 3D printed golf ball by Nike. This image shows the difference layers and materials in a golf ball [32].

In some manufacturing cases, several materials with different characteristics must be combined. 3D printing is an approach that enables smooth material transitions and combination of materials. A smooth transition between materials is ideally possible when the materials have similar properties. For example, Nike has developed a novel fabrication method for golf balls utilising the capability of 3D printing to tailor the shape and structure of an individual layer, thus using several different materials inside the ball [33]. Different layers and materials in a 3D printed golf ball are shown in Figure 5. Nike is using an elastomeric material for an inner core and a rigid material for an outer core. This enables combining soft and hard characteristics for optimal results.

As 3D printing is entirely a digital fabrication process, there is no need to initially make large and costly application specific preparations, such as masks or extrusion moulds, for a new design or product. The largest costs come in the form of the printer, materials and labour. This revolutionizes the traditional “economy of scale” in manufacturing: price per product is the same regardless of the production quantity. Therefore, customized products are cheaper to make with 3D printing than in large-scale manufacturing. In mass production using 3D printing, the number of parts printed does not affect the price. However, in traditional production, the price of a unit decreases with increased manufacturing frequency. The same factors make 3D printing an ideal technique for rapid prototyping and design testing.

Interestingly, 3D printing can also be used to repair damaged structures in a part since material can be added to specific locations that needs to be repaired. As a result, it is possible to fix damaged products and structures rather than having to completely replace the part, thus reducing wasted material and energy usage. A prime example is in the fabrication of titanium parts where the manufacturing process involves the machining of a part from a larger piece of titanium. This can be a time consuming process and result in large amounts of waste material. With 3D printing it is possible to create the same part on a layer-by-layer basis and then remove any excess material via machining. The same process can be used to repair a broken segment of a part by first removing the broken segment and then 3D printing a replacement segment using the same material or even a new material. In conjunction with heat treatments, parts repaired using 3D printing and subsequent machining can yield parts that feel and appear as new.

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RELEVANCE OF 3D PRINTING FOR TONY STARK

Rapid prototyping, intricate light and durable new structures and quick damage repair are all phrases that could be easily associated with Tony Stark and the Iron Man suit. In the films of the Marvel Cinematic Universe (MCU), we are not directly shown how Tony Stark fabricates the various Iron Man armours that he uses to face off against villains such as Whiplash, Loki and Ultron. Nonetheless, 3D printing sections of the suit would offer a number of interesting benefits to Tony Stark. In the 2012 film *The Avengers* [4], J.A.R.V.I.S., Tony Stark's artificial intelligence assistant, informs Stark that a new armour is in preparation. However, we are not informed of the process used by Stark. Given that the suit is made in Stark Tower, it is highly unlikely that Tony uses a large assembly facility consisting of metal works and casting. An obvious choice for Stark would be to use a 3D printing facility along with a small machining shop that is located in one of the top-level floors, close to the Avengers' headquarters.

In the 2015 film *Avengers: Age of Ultron* [5], Tony uses the Hulkbuster suit, a special add-on build for the Iron Man, and also known as Veronica, that is stored in a low-orbiting satellite for easy and fast global deployment. Rapid prototyping with 3D printing would enable Stark to fabricate new Hulkbuster suits as required. These suits can then be delivered to the low-orbiting satellites using a Soyuz-style spacecraft that would simply insert itself into the satellite. This would allow Stark to reuse the satellite, which could also have been 3D printed, while saving on materials, time and decreasing space junk or debris. It is conceivable that any damage caused to the Hulkbuster during combat could be repaired on the fly using in-built 3D printing technologies. Another approach would be to 3D print the parts from self-healing materials such that the materials could repair themselves during combat [34].

For Tony Stark, 3D printing would allow for even lighter and mechanically stronger suits made from exotic materials such as self-healing materials, graphene-based materials or advanced titanium-gold alloys, making them faster, more agile and more durable. Tailored surface structures could improve aerodynamics and even be made to reflect light and energy based attacks [35].

FUNCTIONAL PRINTING: INKJET-PRINTING

WHAT IS FUNCTIONAL PRINTING?

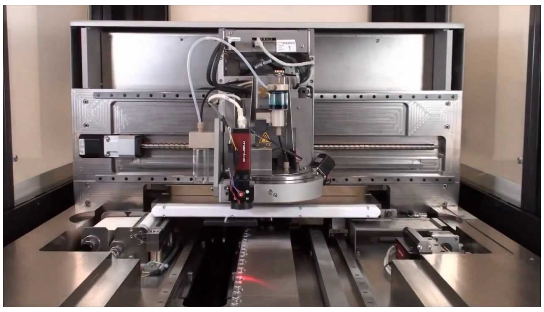

Figure 6: Inkjet-printer by Meyer Burger Netherlands B.V.

3D printing can be used to fabricate some interesting and novel parts such as golf balls (Figure 5). However, the majority of these parts simply act as support structures and do not fulfil any other tasks. To use these parts for other applications such as in electronic devices, suitable functional materials are needed. One method of fabricating functional devices and patterns is via inkjet-printing, which uses a similar technology to that found in regular home printers. However, the difference is that high quality and precision printheads enable the use of functional inks and accurate deposition

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methods [36]. Figure 6 shows inkjet-printing equipment manufactured by Meyer Burger Netherlands B.V. that uses a moving printhead and substrate table similar to 3D printer design shown in Figure 1.

Functional inks can range from conductive nanoparticle metals to magnetic and semiconductive composites [37]. Inkjet-printing is an accurate method for material deposition and arrangement that enables fabrication of complex multilayer functional devices [38, 39]. Picolitre-sized printheads, which are printheads that can dispense very small ink droplets, enable relatively small features to be printed and high pattern definition [40]. An inkjet-printed conductive trace forming a transistor on stretchable elastomer is shown in Figure 7.

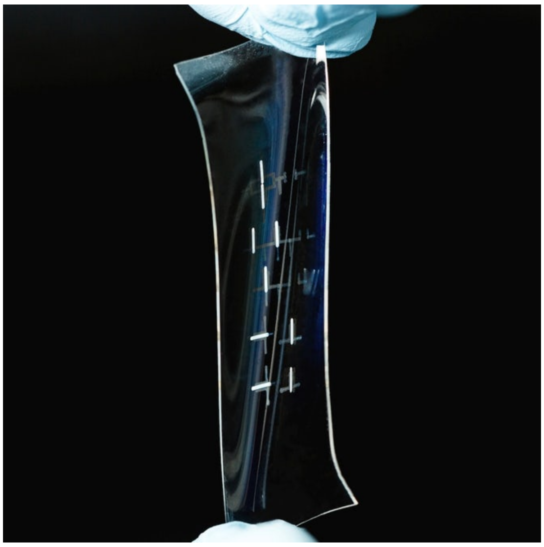

Figure 7: Inkjet-printed transistor on a stretchable elastomer substrate [41].

The inkjet-printing method is a non-contact fabrication method given that the printhead does not need to be in physical contact with the substrate material. Non-contact means that printing can also be done on a variety of topographies and geometries, which no other printing approach can achieve. This allows for the printing of functional patterns on a variety of materials, such as those with an irregular topography or materials that are highly sensitive to physical contact. For example, some rubber-like elastomers and very thin substrates are too touch-sensitive to be used with some production technologies. An example of an inkjet-printed conductive pattern printed on varied topography or non-flat substrate is presented in Figure 8.

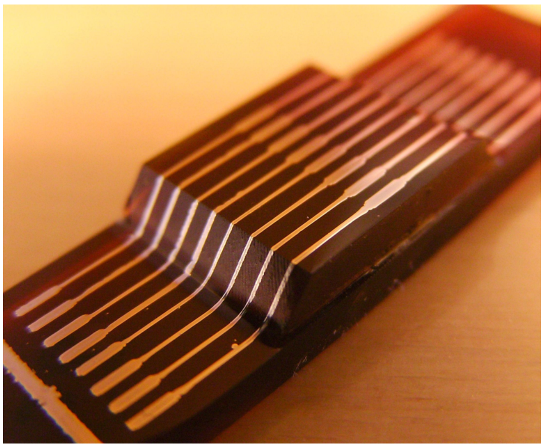

Figure 8: Inkjet-printed conductive pattern on a varied topography [42]. Linewidth of the silver traces is about 200 μm and height difference between the two levels in the image is 2mm.

Inkjet-printing is an entirely additive manufacturing process since the material is only added and not removed as with traditional electronics manufacturing processes. As a result, inkjet-printing saves on material and energy usage. The method also allows for the easy repair of damaged patterns as products do not need to go through several process steps such as etching or chemical treatments given that such treatments would actually damage the printed pattern.

Inkjet-printing, just like 3D printing, is a completely digital process since the design is stored as a digital file and there is no need to make physical masks or moulds. As with 3D printing, this enables rapid prototyping and eliminates the traditional "economy of scale" view. New designs can be made by simply modifying the digital image. This makes product customization as trivial as mass production is in the manufacturing industry today.

FUNCTIONAL PRINTING FOR TONY STARK

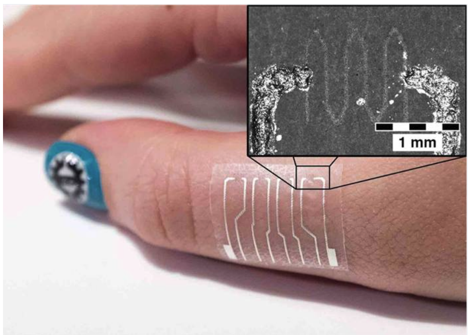

Figure 9: Inkjet-printed thermal sensor element on polyurethane substrate [43].

Inkjet-printing can be used to make functional patterns on very thin and stretchable substrate materials, such as a poly(dimethylsiloxane) (PDMS). PDMS-based electrical structures have been shown to endure stresses up to 188%. The transistor in Figure 7 endures repeatable stretching up to 50% with no significant decrease in electrical properties [41, 44]. Electronic devices made from these materials can be kept very close to the skin for long times without discomfort, making these devices optimal for different sensor functions [43, 45]. As of yet, it has not been revealed in the Marvel films exactly how Tony Stark controls the Iron Man suit. The use of very thin, stretchable and conformal sensor elements on either his skin or clothing certainly offer very viable methods for Stark to control the suit. Nonetheless, printed sensors in the suit would provide Stark with a very effective way of gathering invaluable data regarding his biological functions, the integrity of the suit and the position of enemies when in battle. Data measured by such sensors could include temperature measurements from his body, external humidity, measure of nearby electric and/or magnetic field, detection of physical motion and vibrations, and the detection and analysis of gases [46].

An example of an inkjet-printed thermal sensor element on stretchable polyurethane substrate is shown in Figure 9 [43]. The stretchable substrate makes the sensor highly conformal and it can be worn on skin without discomfort. The functional sensor element is made by inkjet-printed ink mixture of graphene and PEDOT:PSS (poly(3,4-ethylenedi-oxythiophene) polystyrene sulfonate) and connected with screen-printed silver ink. Biosensors are, in general, a popular research topic. For example, printed glucose and bacteria sensors can be fabricated with both inkjet- and screen-printing [47-49].

Just as sensors are able to sense their environment, actuators are able to affect their surroundings. Actuators can also be fabricated with inkjet-printing. The simplest actuators to manufacture are thermal and mechanical, *i.e.* to heat or move a target near the actuators surroundings [45, 50]. When sensors and actuators are combined with computational elements they can form smart systems that can sense, react and interact with their surroundings. With the development of new smart materials and smaller and more powerful computational elements, these reactive smart systems can advance even further. If these fairly simple systems also have communication capabilities, they can work together and form what is called swarm or collective intelligence that are far more capable and powerful than the single units [51]. These types of tools and equipment would prove invaluable to Tony Stark on his missions with the Avengers.

Inkjet-printing can also be used to fabricate optical elements such as microlenses

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that can change and control the optical properties of the surface. When microlenses are produced on a substrate they can be used to control the behaviour of light on the surface; either the light generated by the device itself or light the surface reflects. In combination with other components, these lenses could be used to create holographic projectors, active camouflage and cloaking devices [52, 53]. Inkjet-printed microlenses are shown in Figure 10. These small lenses, typically with a diameter of 100 μm, and can be produced in highly repeatable patterns on a surface.

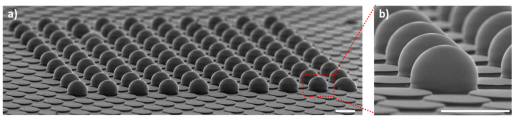

Figure 10: Scanning electron microscope (SEM) image of inkjet-printed microlens array. (a) Whole microlens array. (b) Close-up on a few individual lenses. In both images the scalebar represents 100 μm [52].

The aforementioned functional printing techniques would be very valuable for Tony Stark. They would help in both changing and adding new capabilities to the Iron Man suit in a much faster and more flexible manner. For example, what if Tony needed a new antenna to transmit and intercept communications at different wavelengths? With functional printing in the Iron Man suit he would be able to almost instantly print a new antenna that could be integrated with existing subsystems. If Tony wanted to allow the suit to become invisible at a certain wavelength, he could 3D print a microlens array for the suit. On occasion Tony may also require customized miniature sensors and actuators. To facilitate this, he could use inkjet-printing to produce single or multiple use sensors in a matter of moments. Such innovative approaches could prove vital to Tony and his allies when facing dangerous enemies.

CONCLUSIONS

Printing methods for the production of both structural and functional parts is becoming an integral approach of not only the prototyping and design of parts but in the establishment of new and sustainable manufacturing approaches [15]. Therefore, it should come as no surprise that Tony Stark would turn to 3D printing methods for the design of new parts and to quickly produce replacement parts for his Iron Man suits. By turning to functional printing, Tony would take advantage of the many benefits of the associated printing methods, allowing him to easily modify his suits for the ever-changing demands he places on his technologies [54]. In this paper, 3D and functional printing approaches have been discussed as two separate technologies. However, recent technological advances seek to combine the benefits of both technologies. This means that both mechanical and electrical structures can be fabricated during the same step, and even embedded into hybrid structures that function as mechanical support structure with associated electrical functionality [55].

As of yet, we have not developed the technology to build a workable Iron Man suit. Nevertheless, we have produced many of the technologies in the suit separately such as the titanium-gold alloy on the front of the suit [35], biosensors, elements of the helmet [56] and the exoskeleton component [57]. The various 3D printing techniques presented in this paper certainly show that 3D printing offers some new and unique benefits in bringing us closer to technological marvels, and, most importantly, making life for Tony Stark and the manufacturing of his Iron Man suits a little easier.

REFERENCES

1. Watts, J., *Spider-Man: Homecoming (motion picture)*. 2017, Sony Pictures/Marvel Studios/Columbia Studios.
2. Fitzgerald, B.W., *Secrets of Superhero Science*. 2016: BW Science.
3. Favreau, J., *Iron Man (motion picture)*. 2008, Marvel Studios.
4. Whedon, J., *The Avengers (motion picture)*. 2012, Marvel Studios.
5. Whedon, J., *Avengers: Age of Ultron*. 2015, Marvel Studios.
6. Russo, J. and A. Russo, *Avengers: Infinity War*. 2018, Marvel Studios.
7. Brown, S.P., et al., *Superhero physiology: the case for Captain America.* Advances in Physiology Education, 2017. **41**(1): p. 16-24.
8. Fitzgerald, B.W., *Using Hawkeye from the Avengers to communicate on the eye.* Advances in Physiology Education, 2018. **42**(1): p. 90-98.
9. Fitzgerald, B.W., *Using superheroes such as Hawkeye, Wonder Woman and the Invisible Woman in the physics classroom.* Physics Education, 2018. **53**(3): p. 035032.
10. Fitzgerald, B.W., *Superhero Science and Technology: A New Open Access Journal.* Superhero Science and Technology, 2018. **1**(1).
11. ASTM, *ISO/ASTM 52900 Additive Manufacturing - General Principles and Terminology*. 2015.
12. Pacchioni, G., *3D printing: May the strength be with you.* Nature Reviews Materials, 2017. **2**.
13. BBCNews. *Scientists 3D-print transparent glass*. 2017 [cited 2018 24-02-2018]; Available from: http://www.bbc.com/news/av/technology-39870829/scientists-3d-print-transparent-glass.
14. LulzBot. *LulzBot TAZ 6*. [cited 2018 25-03-2018]; Available from: https://www.lulzbot.com/store/printers/lulzbot-taz-6.
15. Lipson, H. and M. Kurman, *Fabricated: The New World of 3D printing*. 2013: John Wiley & Sons.
16. 3DPrinting.com. [cited 2018 24-02-2018]; Available from: https://3dprinting.com/what-is-3d-printing/.
17. Kodama, H., *Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer.* Review of Scientific Instruments, 1981. **52**: p. 1770-1773.
18. Bártolo, P.J., *Stereolithography: Materials, Processes and Applications*. 2011: Springer US.
19. Bourella, D.L., et al., *Performance limitations in polymer laser sintering.* Physics Procedia, 2014. **56**: p. 147-156.
20. Molitch-Hou, M. *T3D Smartphone 3D Printer Could Democratize 3D Printing*. 2017 [cited 2018 24-02-2018]; Available from: https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/14186/T3D-Smartphone-3D-Printer-Could-Democratize-3D-Printing.aspx.
21. Formlabs. *Creating Camera Lenses with Stereolithography*. [cited 2018 24-02-2018]; Available from: https://formlabs.com/blog/lenses-3D-printed-formlabs/.
22. General_Electric. *The Blade Runners: Take A Look Inside This Factory 3D Printing Jet Engine Parts*. 2017 [cited 2018 24-02-2018]; Available from: https://www.ge.com/reports/future-manufacturing-take-look-inside-factory-3d-printing-jet-engine-parts/.
23. Shekhawat, A. and R.O. Ritchie, *Toughness and strength of nanocrystalline graphene.* Nature Communications, 2016.
24. Chandler, D.L. *Researchers design one of the strongest, lightest materials known*. 2017 [cited 2018 24-02-2018]; Available from: http://news.mit.edu/2017/3-d-graphene-strongest-lightest-materials-0106.
25. Zhao Qin, G.S.J., Min Jeong Kang and Markus J. Buehler, *The mechanics and design of a lightweight three-dimensional graphene assembly.* Science Advances, 2017. **3**.
26. 3DMatter. *What is the influence of infill %, layer height and infill pattern on my 3D prints?* 2015 [cited 2018 24-02-2018]; Available from: http://my3dmatter.com/influence-infill-layer-height-pattern/.
27. Magics, M. *Materialise Magics: Data preparation tool for Additive Manufacturing*. 2018 [cited 2018 06-02-2018].
28. Cults3d. *Captain America low polygon superhero STL-model*. [cited 2018 06-02-2018].
29. Hernandez, R., et al., *Analysing the tensile, compressive, and felural properties of 3D printed ABS P430 plastic based on printing orientation using fused desposition modeling*, in *Solid Freeform Fabircation 2016: Proceedings of the 27th Annual International Solid Freeform Fabrication Symposium*. 2016.
30. Cotell, C.M., J.A. Sprague, and F.A. Smidt, *ASM Handbook, Volume 5*. 1994: ASM International.
31. Doyle, G. *Metal 3D Printed Concept F1 Cylinder Head*. 2018 [cited 2018 2018-02-24]; Available from: https://www.linkedin.com/pulse/metal-3d-printer-concept-f1-cylinder-head-geoffrey-doyle/.
32. Nike. *Innovation shapes the new Nike RZN tour golf ball*. 2018 [cited 2018 25-03-2018]; Available from: https://news.nike.com/news/nike-rzn-tour-golf-ball.
33. Smock, D. *Nike Develops Improved 3D-Printed Golf Ball*. The Molding Blog 2017 [cited 2018 24-02-2018]; Available from: http://www.themoldingblog.com/2017/02/21/nike-develops-improved-3d-printed-golf-ball/.
34. Milena Nadgorny, Z.X.a.L.A.C., *2D and 3D-printing of self-healing gels: design and extrusion of self-rolling objects.* Molecular Systems Design & Engineering, 2017. **2**: p. 283-292.
35. Svanidze, E., et al., *High hardness in the biocompatible intermetallic compound β-Ti3Au.* Science Advances, 2016. **2**(7).
36. Molesa, S., *Ultra-Low Cost Printed Electronics*, in *Electrical Engineering*. 2006, University of California at Berkeley: Berkeley, California, USA.
37. Gerard Cummins, M.P.a.Y.D., *Inkjet Printing of Conductive Materials: a Review.* Emerald Insight, 2012. **38**(4): p. 193-213.
38. Benjamin C. Cook, B.T., James R. Cooper and Manos M. Tentzeris, *Multilayer Inkjet Printing of Millimeter-Wave Proximity-Fed Patch Arrays on Flexible Substrates.* IEEE Antennas and Propagation Letters, 2013. **12**: p. 1351-1354.
39. Jorge Alaman, R.A., Jose Ignacio Pena and Carlos Sanchez-Somolinos, *Inkjet Printing of Functional Materials for Optical*

and Photonic Applications. Materials (Basel), 2016. **9**.
40. Joshua Lessing, A.C.G., S. Brett Walker, Christoph Keplinger, Jennifer A. Lewis and George M. Whitesides, *Inkjet Printing of Conductive Inks with High Lateral Resolution on Omniphobic "RF Paper" for Paper-Based Electronics and MEMS.* Advanced Materials, 2014. **26**(27): p. 4677-4682.
41. Le Cai, S.Z., Jinshui Miao, Zhibin Yu and Chuan Wang, *Fully Printed Stretchable Thin-Film Transistors and Integrated Logic Circuits.* ACS Nano, 2016. **10**(12).
42. Koskinen, S., *Johdinkuviointi kolmiulotteiselle pinnalle*, in *Department of Electronics*. 2009, Tampere University of Technology: Tampere, Finland.
43. Tiina Vuorinen, J.N., Timo Kankkunen, Thomas M. Kraft and Matti Mäntysalo, *Inkjet-Printed Graphene/PEDOT:PSS Temperature Sensors on a Skin-Conformable Polyurethane Substrate.* Scientific Reports, 2016. **6**.
44. Lipomi, D.J., et al., *Electronic Properties of Transparent Conductive Films of PEDOT:PSS on Stretchable Substrates.* Chemistry of Materials, 2012. **24**(2): p. 373-382.
45. R. Chad Webb, R.M.P., Philippe Bastien, Joshua Ayers, Juha Niittynen, Jonas Kurniawan, Megan Manco, Athena Lin, Nam Heon Cho, Viktor Malyrchuk, Guive Balooch and John A. Rogers, *Thermal Transport Characteristics of Human Skin Measured In Vivo Using Ultrathin Conformal Arrays of Thermal Sensors and Actuators.* PLOS One, 2015. **10**(2).
46. Ando, B. and S. Baglio, *All-Inkjet Printed Strain Sensors.* IEEE Sensors Journal, 2013. **13**(12): p. 4874-4879.
47. Ertl, P., et al., *Rapid identification of viable Escherichia coli subspecies with an electrochemical screen-printed biosensor array.* Biosensors and Bioelectronics, 2003. **18**(7): p. 907-916.
48. L. Setti, A.F.-M., I. Mencarelli, A. Filippini, B. Ballarin and M. Di Biase, *An HRP-based amperometric biosensor fabricated by thermal inkjet printing.* Sensors and Actuators B: Chemical, 2007. **126**(1): p. 252-257.
49. Rafiq Ahmad, M.V., Nirmalya Tripathy and Yoon-Bong Hahn, *Wide Linear-Range Detecting Nonenzymatic Glucose Biosensor Based on CuO Nanoparticles Inkjet-Printed on Electrodes.* Analytical Chemistry, 2013. **85**(21): p. 10448-10454.
50. Oliver Pabst, J.P., Erik Beckert, Ulrich S. Schubert, Ramona Eberhardt and Andreas Tünnermann, *All inkjet-printed piezoelectric polymer actuators: Characterization and applications for micropumps in lab-on-a-chip systems.* Organc Electronics, 2013. **14**(12).
51. Brambilla, M., et al., *Swarm robotics: a review from the swarm engineering perspective.* Swarm Intelligence, 2013. **7**: p. 1-41.
52. Loïc Jacot-Descombes, V.J.C., Arne Schleunitz, Susanne Grützner, Jan J. Klein, Jürgen Brugger, Helmut Schift and Gabi Grützner, *Organic-inorganic-hybrid-polymer microlens arrays with tailored optical characteristics and multi-focal properties.* Optics Express, 2015. **9**(11).
53. Hamanaka, K. and H. Koshi, *An Artificial Compound Eye Using a Microlens Array and Its Application to Scale-Invariant Processing.* Optical Review, 1996. **3**(4): p. 264-268.
54. Ehab Saleh, F.Z., Yinfeng He, Jayasheelan Vaithilingam, Javier Ledesma Fernandez, Ricky Wildman, Ian Ashcroft, Richard Hague, Phill Dickens and Christopher Tuck, *3D Inkjet Printing of Electronics Using UV Conversion.* Advanced Materials Technologies, 2017. **2**(10).
55. Zastrow, M., *Four-in-one 3D printer paves way for custom-made robots and phones.* Nature, 2018. **555**: p. 569.
56. Song Lv, et al., *Design, fabrication and feasibility analysis of a thermo-electric wearable helmet.* Applied Thermal Engineering, 2016. **109**: p. 138-146.
57. Bogue, R., *Robotic Exoskeletons: a Review of Recent Progress.* Industrial Robot: An International Journal, 2015. **42**(1): p. 5.